A REVIEW OF MAGNETIC SENSOR-BASED POSITIONING TECHNIQUES FOR CAPSULE ENDOSCOPY

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ABSTRACT:

The capsule endoscope, as one of important equipment in screening the entire spectrum of digestive tract disease diagnosis, has largely compensated for the limited of vision field and poor patient experience of wired endoscopes. In order to better develop the clinical application of capsule endoscope and assist doctors in the diagnosis and treatment of gastrointestinal diseases, there is an urgent need to solve a key scientific problem, that is obtaining the position information of capsule endoscope in the body. This article reviews the research evolution of the capsule endoscope based on magnetic localization through the last 10 years and describes notable problem, as well as technological challenges to overcome. Besides that, the article also presents the future development in capsule endoscopy localization technology based on magnetic sensors, for further developing capsule endoscopy localization and surgical navigation.

1. INTRODUCTION

It has been 22 years since the appearance of the first commercial capsule endoscopy(Iddan, Meron, Glukhovsky, & Swain, 2000) by Israel in 2001. Capsule endoscopy (CE), as one of the most usual, non-invasive and patient-friendly visualization diagnostic techniques of gastrointestinal (GI) tract, has been used in medical examination of some small-intestinal and colon diseases, such as gastrointestinal bleeding, small-intestinal polyps and tumors, which are difficult for conventional endoscopy because of narrow and curved gastrointestinal tract. Nowadays, there are several leading companies in the global market of CE, which provide diagnostic tools for non-invasive exploration of the GI track. Two of these companies, they are ANHON Technologies Company and JIFU Medical Technologies Company(Lai et al., 2020), have produced the magnetically controlled capsule endoscopy (MCE), which make it possible to display the stomach in all round, using an external magnetic field to manipulate the motion of capsule endoscopy in the stomach. Despite years of research and development, as a third-level medical device for human intake, as shown in the Figure 1 most capsule endoscopes are cylinders within 27mm in length and 13mm in diameter, weighing only a few grams, with cameras, LED lights, batteries, transmitters, antenna and magnets of MCE (Meng et al., 2004; Vasilakakis, Koulaouzidis, Marlicz, & Iakovidis, 2020). Additional devices for CE system varies considerably. According to the investigation(Vasilakakis et al., 2020), among the capsule endoscopes currently used for medical examination, magnetic controlled capsule endoscopes are more complex in function and structure compared with other capsule endoscopes, as shown in Figure 2 The left picture of the Figure 2 is NaviCam magnetic controlled capsule endoscopes of ANHON Technologies Company (Ching, Tai, Hale, Sidhu, & McAlindon, 2018), and its structure(Adler & Gostout, 2003) includes: control console, , computer workstation (which includes with medical grade professional image display and auxiliary video reading system), portable receiver, wireless endoscope. The right picture of the Figure 2 shows the standing magnetic control endoscopy of JIFU Medical Company(Lai et al., 2020). Compared with MCE produced by the ANHON, the hand-held MCE control device is more convenient to operate.

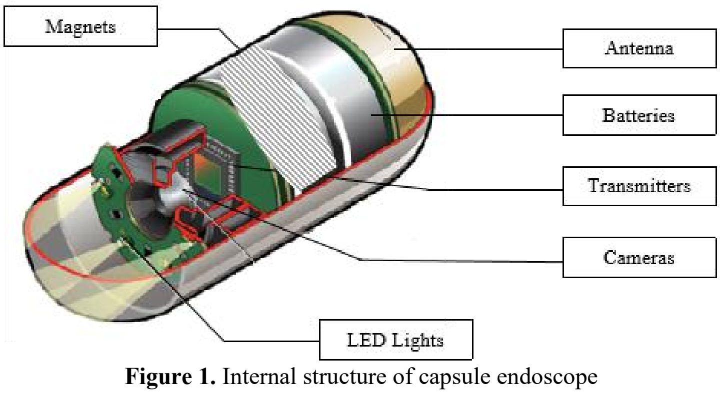

Figure 1. Internal structure of capsule endoscope

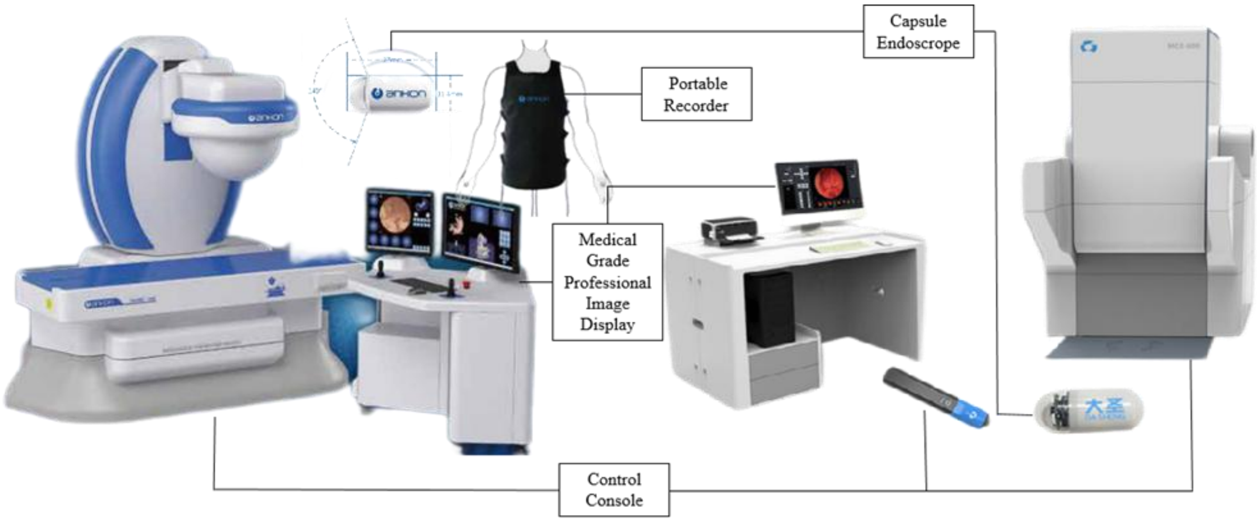

Figure 2. Compositions of MCE

Besides the research of the active motion mechanism (Fu, Guo, & Guo, 2017; Gao et al., 2015; Lee et al., 2014) of CE like the MCE, which makes it possible that endoscopists are able to interfere in the movement of the capsule robots, when it moves in the lumen of the GI tract propelled by contractions. there are some other research aspects. As the review (Vasilakakis et al., 2020) summarized, some research groups have developed accurate and reliable automated abnormality detection software (Ghosh, Fattah, Wahid, & Engineering, 2018; D. K. Iakovidis & Koulaouzidis, 2015), which can free the doctors from the time-consuming task of review CE video. Besides that, intense research activity has been developed aiming to achieve the noninvasive or minimally biopsy(Son, Gilbert, & Sitti, 2020; Yim, Gultepe, Gracias, & Sitti, 2013), the therapeutic function(Leung et al., 2016; Z. Li et al., 2016), the targeted drug delivery and minimally invasive surgery (Z. Li et al., 2016). In fact, all of these research aspects are just in order to solve one medical difficulty, that is, the capsule endoscopes are used to non-invasive or minimally invasive diagnose digestive tract diseases, identify the location of lesions and achieve local fixed-point treatment. In order to achieve these goals, the basic problem to be urgently solved is the acquisition of accurate position and orientation information of the capsule endoscope in the human body.

Our objective of the research is to find a positioning method with the safety and the feasibility. In specific, the following objectives of the proposed:

- Make a simple introduction about the capsule endoscopy positioning technology;
- Survey the state of art at home and abroad of the CE localization method based on magnetic sensors in the design of hardware system and the algorithms of localization solution;
- Evaluate the advantages and disadvantages of magnetic sensor as single signal source to position capsule endoscope in detail;
- Put forward that there are two kinds of method to improve the application effective of capsule endoscope positioning technology with magnetic sensor. One is to fuse other positioning source, such as IMU and visual information.

2. MAGNETIC SENSORS-BASED POSITIONING TECHNIQUES

2.1 Positioning Techniques Classification According Signal Source

According to reviewed for the latest ten-years papers in the google scholar website, the web of science, IEEE/IET electronic library and the Elsevier ScienceDirect. As shown in Figure 3, according to the signal source, current capsule endoscope localization approaches mainly include: ① radiofrequency (RF) localization including with time estimation with respect to anatomic landmarks (Trung Duc et al., 2014) and triangle positioning principle (Jeong, Kang, Pahlavan, & Tarokh, 2017), ② magnetic localization methods including with magnetic sensors-based positioning(Fu, Wang, Guo, Guo, & Cai, 2020; Kim, Kim, Park, Choi, & Kim, 2020; Wang, Song, Liu, & Meng, 2021; Xu, Kong, Ye, & Xu, 2017) (PM) and magnetic actuation technology(Sendoh, Ishiyama, & Arai, 2003) (AM) , ③ inertial navigation and positioning(Ren & Kazanzides, 2012; Vedaei & Wahid, 2021) (IMU), ④ visual positioning (Dimitris K Iakovidis et al., 2016; Spyrou & Iakovidis, 2014; Spyrou, Iakovidis, Niafas, & Koulaouzidis, 2015) and ⑤ medical imaging assistant positioning (MIA)(Geng & Pahlavan, 2015; Sun et al., 2012) based on Computerized Tomography (CT), Magnetic Resonance Imaging (MRI),or Ultrasound, ⑥ Multi-source information fusion positioning technology(Bao, Pahlavan, & Mi, 2015; Turan, Almalioglu, Gilbert, et al., 2018; Turan, Almalioglu, Ornek, et al., 2018; Vedaei & Wahid, 2021).

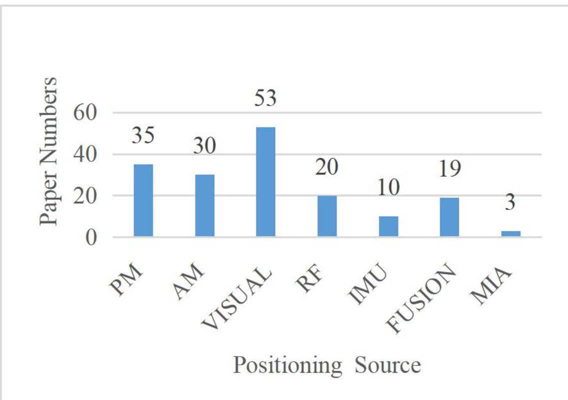

Figure 3. Histogram of CE positioning methods

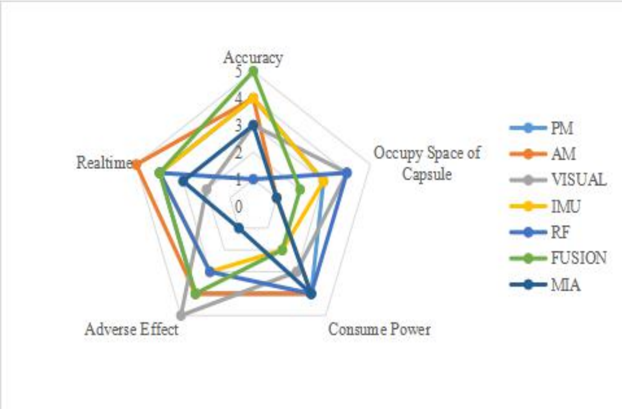

Figure 4. Radar diagram of performance comparison

The figure 4 is the radar statistical diagram of performance comparison of different localization methods. There are five performance indexes, and every index have 5 levels. The higher the number of the performance index, the better the technology performance in this aspect. As shown in the figure4, the medical imaging assistant positioning method has the lowest overall performance. WCE localization system based on medical imaging technologies including CT, MRI, and US can reconstruct three - dimensional model of digestive tract. However, the continuous aided imaging over several hours can restrict the patient's movement, and radioactive material can cause irreversible damage to the human body. According to surgical experts, the human digestive tract has individual differences, especially after open surgery patients have slight changes in organ position compared with normal people. Therefore, there may be a large error in calculating CE location throw time estimation based on biomarker points, one of RF methods. It has been reported (Fischer, Schreiber, Levi, & Eliakim, 2004; Hu, 2006) that 62.0% samples have 40 mm or better accuracy; 87.0% samples have 60 mm or better accuracy; the average error is 37.7 mm. Its triangle measurement accuracy seems to be too low. In author's opinion, another reason causing the lowest accuracy is that different absorption rate of radiofrequency signal by human tissues and organs. Although the lowest localization accuracy, some research group (Bao et al., 2015; Khan et al., 2019; Nafchi, Goh, & Zekavat, 2014; Ye, 2013; Zhou, 2015) still do many researches to improve positioning accuracy. The RF system is also used to transmit the captured images, this localization module has the advantages that it does not require any additional equipment and has low power consumption. The accelerometer and gyroscope in the inertial sensor can accurately perceive the changes in the motion state of the CE. The miniaturized micro-electro-mechanical systems (MEMS) makes it possible to embed the CE with limited volume in the inertial sensor. The precision of the CE positioning technology based on inertial navigation has been greatly improved compared with RF technology (Jeong et al., 2017). Through the investigation of the literature on capsule endoscopy positioning technology in the past decade, vision positioning technology with capsule video is popular with researchers. This is partly due to the emergence of many high-performance SLAM technologies, and partly due to the need for portable devices to increase patient comfort, visual positioning, without additional signal transmitting and receiving equipment, just meets this need. Observing from the above researches on visual positioning technology, it is easy to find that there are the following limitations and assumptions in the experiment design. The first, the GI is fixed in shape and has invariance. The second, Continuous key frames have rich and stable texture features and good illumination conditions. The third, there is no liquid or debris content. However, on the contrary, as shown in the figure5 the real GI is flexible and deformable because of the intestinal peristalsis, which is contrary to the assumptions of rigid SLAM. Furthermore, the real GI environment is full with liquid and residue, and has the texture-less nature and strong specular reflections of the digestive tract surface. Therefore, only using visual information to positioning CE is still in the experimental exploration period, far from the practical application.

Figure 5. The Videos Frame of CE

As shown in the figure 3, another widely studied technique is magnetic sensors-based localization, and the controllable capsule endoscope （as shown in the figure 2）currently on the market for clinical diagnosis is also based on magnetic field to control capsule movement. Why the magnetic localization methods have been popular until today? The next part of the article will produce the magnetic localization methods in detail.

2.2 The Development of Magnetic Sensors-based Localization

Magnetic technology has been widely used in the medical field in recent years because of its non-contact control, not affected by human tissue, no difference in transmission of human tissue, small size and easy to control. For example, magnetic navigation technology has significant clinical effects in the application of cardiovascular intervention, bronchoscopy, neurosurgery and magnetic capsule endoscopy (Barducci, Pittiglio, Norton, Obstein, & Valdastri, 2019; J. Li et al., 2018; Shi, Liu, Song, Wang, & Meng, 2021). Therefore, since the birth of CE, the use of magnetic field to make sure the position and posture of capsule endoscope in human GI tract has been the focus of researchers at home and abroad. As shown in the figure 4, apart from the magnetic actuation capsule endoscopy system used in hospital, the magnetic sensors-based localization (PM) performs well in accuracy and safety. The CE magnetic localization mainly relies on the human body's own mechanism such as gastrointestinal peristalsis gravity traction to provide power for its movement in the human body. Compared with other methods, this technology, which uses static magnetic field to determine the position parameters and trajectory of wireless capsule endoscope, has the characteristics of reliable principle, simple, unlimited user activity and high positioning accuracy. As shown in the figure 6, the CE, which enclose a permanent magnet, moves in a patient's GI tract, and creates a magnetic field. The field intensities at some spatial points are measured by magnetic sensor array placed around the patient's body. An ideal dipole, called as magnetic dipole model(Hu et al., 2016b; Schlageter, Besse, Popovic, Kucera, & Physical, 2001) to establish the position state equation, and solve the equation by optimization algorithm to solve the position. Researchers mainly focus on the hardware system development, position calculation algorithm improvement, software development and experimental platform construction of magnetic sensor-based localization technology for capsule endoscope. Researchers have carried out in-depth studies on the influence of magnetic sensor sequence and distribution mode on positioning results(Hu, Li, Song, Zhang, & Meng, 2010; Moussakhani, Ramstad, Flam, Balasingham, & Ieee, 2012; X. Wang, M. Q. H. Meng, & C. Hu, 2006), magnetic interference robustness enhancement of magnetic positioning method, human motion compensation and other aspects. Algorithms mainly involved include Gauss-Newton algorithm, Levenberge-Marquardt nonlinear algorithm (Hu, Yang, Chen, Meng, & Dai, 2008; Schlageter et al., 2001), nonlinear least squares algorithm, particle swarm optimization, (Yang, Hu, Li, Meng, & Song, 2010), genetic algorithm, simulated annealing algorithm and other optimization algorithms (Hu et al., 2010). In order to better display three-dimensional motion trajectory and evaluate positioning and orientation accuracy, Professor CHEN's team from TIANJIN University and professor HU 'S team from ZHEJIANG University developed openGL magnetic positioning software and C++ magnetic positioning software(Hu et al., 2010) respectively, and built an experimental platform for estimating static positioning and orientation measurement accuracy and dynamic positioning accuracy.

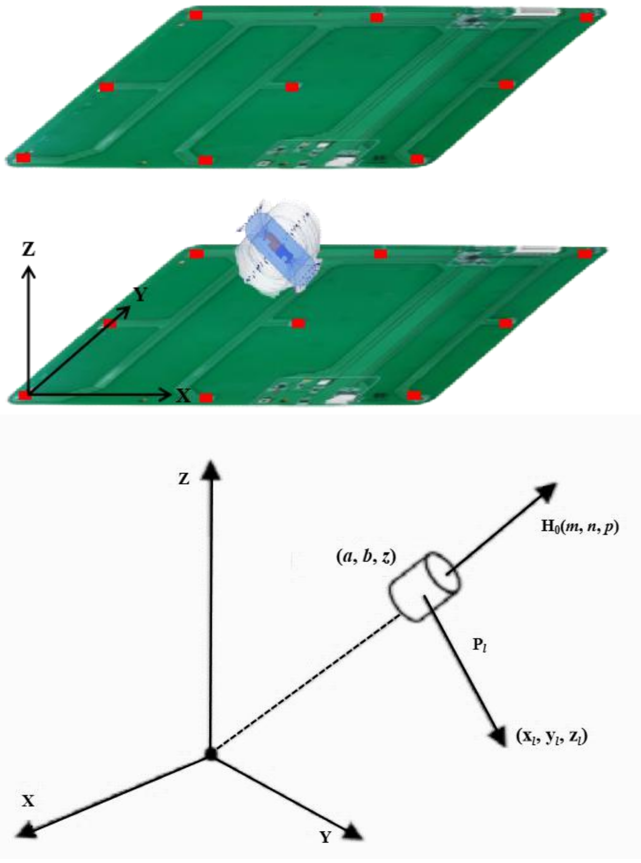

Figure 6. The diagrammatic drawing of magnetic sensor-based localization principle and the magnetic dipole model

2.2.1 Hardware Development

According to the specific distribution law of permanent magnet magnetic field, Professor HOU from CHONGQING University designed a positioning system of micro-diagnosis and treatment device *in-vivo* based on permanent magnet detection(Wensheng, Xiaolin, Chenglin, Xiaoyan, & Xudong, 2004). The system will be sensitive to plus magnetic field direction and size, can detect three orthogonal direction magnetic field component at the same time sequence of hall sensor in eight spatial coordinates of known position, target permanent magnet in the in vitro testing more space magnetic field distribution, and then according to the calculation of permanent magnet magnetic dipole model of spatial location, according to magnetic dipole model calculating target space position relative coordinates, So as to realize the positioning of the micro-diagnosis and treatment device in the body. In order to realize the positioning of wireless capsule endoscope based on permanent magnet multi-point magnetic field detection and analysis, Professor Hou proposed a technology based on MEMS to realize dynamic tracking of micro drug release device using magnetic positioning principle(Wu et al., 2008). The PVC plastic tube was used to simulate the intestinal experiment, and the magnetic field changes were measured by magnetic sensor when the permanent magnet moved in the tunnel. The position parameters of the permanent magnet at each time were calculated and smoothed, and the movement track of the permanent magnet was plotted. In view of the characteristics of low sensitivity and short effective detection distance of Hall magnetic sensor in reference, Dr. HE from Shanghai Jiaotong University used HMC023 reluctance sensor developed by Honeywell with high sensitivity, high resolution and ability to measure weak magnetic field to detect the magnetic field strength of permanent magnets (Xudong, 2006). Based on the above principle of magnetic field positioning micro-diagnosis and treatment equipment, Professor Yan (JIANG, YAN, TIAN, & WANG, 2005) proposed a method of continuous tracking of the position of wireless capsule endoscope in vivo for external static magnetic field detection. Record in vitro six capsule interior permanent magnet magnetic sensors at each sampling instant in sensor location under the magnetic field intensity, according to magnetic dipole model to establish permanent magnets position and attitude between the magnetic induction intensity and nonlinear equations, and by using the genetic algorithm for solving nonlinear equations capsule, body position and posture. In the simulation experiment, in order to accurately simulate the motion track of the wireless endoscope in the body, a 3D model of the human torso was established by using human tomographic medical image and digital image processing technology. The distance error of the track was within 8mm and the direction error was within 7 degrees.

2.2.2 Optimization Algorithm

Professor Hu Chao from Zhejiang University began to study wireless capsule endoscope positioning technology in 2004, and his team has more scientific research achievements in this direction. Professor Hu used magnetic sensor array to detect the magnetic induction intensity of permanent magnet inside M2A capsule, established nonlinear equations by using magnetic dipole model, established appropriate sensor array, and selected optimization algorithm with fast and strong anti-noise performance to calculate 3D position coordinates and 2D direction parameters of the capsule (Hu, 2006; Schlageter et al., 2001). Professor HU compared The local optimization algorithm of Powell and Downhill Simplex, Location error, execution time and dependence on initial value of Direct, Multilevel Coordinate Search and Levenberg-Marquardt global optimization algorithms(X. N. Wang, M. Q. H. Meng, & C. Hu, 2006). It is found that Levenberg-Marquardt algorithm can obtain relatively high accuracy and calculation speed at the same time in the experimental process. the paper (X. Wang et al., 2006) is found that the positioning accuracy of 3-axis Hall sensors is higher than that of single-axis and dual-axis Hall sensors, and increasing the number of sensors is helpful to improve the positioning accuracy. The positioning accuracy of the 2D array composed of 16 3-axis Hall sensors used in literature can reach 87% less than 6mm, and the average position error is 37.7mm. In his doctoral thesis (Hu, 2006), Professor HU established an error model to calibrate the sensitivity of the sensor and adjust its position and direction errors as well as nonlinear errors. Literature (Hu et al., 2016a) corrected near field error and human interference error in passive magnetic positioning algorithm by setting reference targets on human body surface. In addition, due to the axial symmetry of magnetic field distribution of permanent magnet, the magnetic sensor cannot sense the change of magnetic field when the magnet rotates around the axis of symmetry, so the permanent magnet positioning technology can only obtain 2D direction information of the heading Angle and pitch Angle of the magnet. Therefore, researchers proposed a positioning technology combining magnetic technology and imaging technology, using image information to obtain the three-dimensional orientation information of the capsule, camera element to calculate the spin Angle of the capsule, and 5D motion parameter changed to 6D motion parameter(Turan, Almalioglu, Ornek, et al., 2018)..

Above all, the accuracy of PM positioning technology based on permanent magnet has a strong correlation with the number and arrangement of sensors. Choosing the appropriate arrangement of sensors can improve the positioning accuracy at the lowest cost. Using the visual information obtained by the s capsule endoscope camera to solve its orientation information can further improve the positioning accuracy. The fusion of magnetic sensor and inertial measurement element makes the positioning accuracy get qualitative change and can ensure the dynamic accuracy in the applicable range.

3. THE FUTURE TREND OF PM POSITIONING

From the above description, it is not difficult to draw the following two conclusions: ① The type, quantity and spatial distribution all influence the accuracy of capsule endoscope localization in digestive tract. ② The optimization algorithm is also an important factor influencing the stability in CE localization. According to the fact that single signal source has its own limitations and the need of capsule endoscope real-time visualization localization, In order to reduce the dependence on measurement accuracy and reduce the redundancy of the algorithm, the author and other researchers try to improve magnetic positioning technology from the direction of multi-source sensor fusion, (including of IMU-magnetic fusion positioning technology and visual-magnetic sensor fusion positioning technology), as well as improvement optimization algorithms.

3.1 Visual-Magnetic Sensor Fusion

It is introduced in Section 2.1 that although it is difficult to determine the position of the capsule in the digestive tract only by using visual information, there is no doubt that the video information of the capsule can restructure the internal texture structure of the digestive tract and provide a basis for visual positioning. Therefore, from 2012 to now, there are nearly 60 academic studies in the international well-known journal or conferences showing the results of this direction. Among them, the visual-magnetic sensor fusion method integrates several advantages of high positioning accuracy, low energy consumption and good visualization effect.

Since 2017, Professor TURAN has studied how to use CE video information for human GI positioning (Turan, Almalioglu, Araujo, et al., 2017) and GI internal texture reconstruction(Turan, Pilavci, Ganiyusufoglu, et al., 2017; Turan, Pilavci, Jamiruddin, et al., 2017). As shown in figure 7 Endo-VMFuseNet (Turan, Almalioglu, Gilbert, Sari, et al., 2017) method proposed an end-to end deep sensor fusion technique consisting of multi-rate long short-term memories (LSTM) for frequency adjustment and a core LSTM unit for fusing the 6-Dof visual odometry based pose information and 5-Dof magnetic sensor based localization information. Results performed on real pig stomach datasets show that the method achieved sub-millimeter precision for both translational and rotational movements and contains advantage of eliminating the need for the separate calibration and synchronization steps of traditional sensor fusion pipelines over traditional sensor fusion techniques. Before the Endo-VMFuseNet, professor TURAN also tried to use the RGB-D camera to obtain the pose information, and made use of the surfel-based dense reconstruction(Turan, Almalioglu, Gilbert, Araujo, et al., 2017) in combination with particle filter based fusion of magnetic and visual localization information. The sophisticated methods for the calibration and synchronization may increase the difficulty, as well as result in improved accuracy of multi-source fusion localization. In author's perspective, the fusion localization system without calibration and synchronization may improve the positioning efficiency, and be popular with the real-time and visualization CE positioning research.

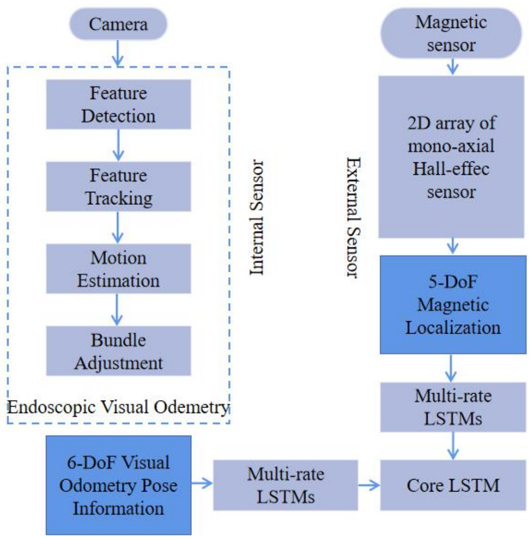

Figure 7. Endo-VMFuseNet pipeline

3.2 IMU-Magnetic Sensor Fusion

As we all known, the Inertial Measurement Unit (IMU) (Y. Li et al., 2021) has been widely used to provide self-contained and continuous motion estimation in intelligent transportation systems. The emergence of The miniaturized micro-electro-mechanical systems (MEMS) has expanded the relevant applications from positioning, navigation, and mobile mapping to micro-spatial localization system *in-vivo* (Kaler & Mintchev, 2006).

A challenge for the LM method is the requirement of accurate initial position and attitude, which is a condition that is difficult to meet in practical applications. To alleviate this issue, some scholars (Salerno, Mulana, Rizzo, Landi, & Menciassi, 2012) have incorporated a MEMS IMU inside the capsule endoscope to determine the capsule attitude when implementing magnetic positioning of active capsule endoscopes. This approach has provided a new idea for solving the CE attitude. In particular, an

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inertial enhanced magnetic positioning approach mentioned by the author can provide exact initial value under the harsh conditions of low observation volume and poor observation quality with magnetometer, as show in figure 8 And the nonlinear least square combined adjustment method based on the per-axial observations of the magnetometer improves the calculation efficiency and reduces the occurrence of gross errors, thus meeting the requirements of real time calculation of the capsule endoscopy positioning system. Compared to the traditional LM approach, the proposed LM method has reduced the position error RMS value from around 35.6 mm to 6.5 mm, with a performance improvement of 81.7 %. Meanwhile, with the proposed method, the maximum position error drops from over 122.9 mm to 16.5 mm, with a performance improvement of 86.6 %. These results have shown the effectiveness of the proposed LM method in enhancing positioning when there is a lack of observations.

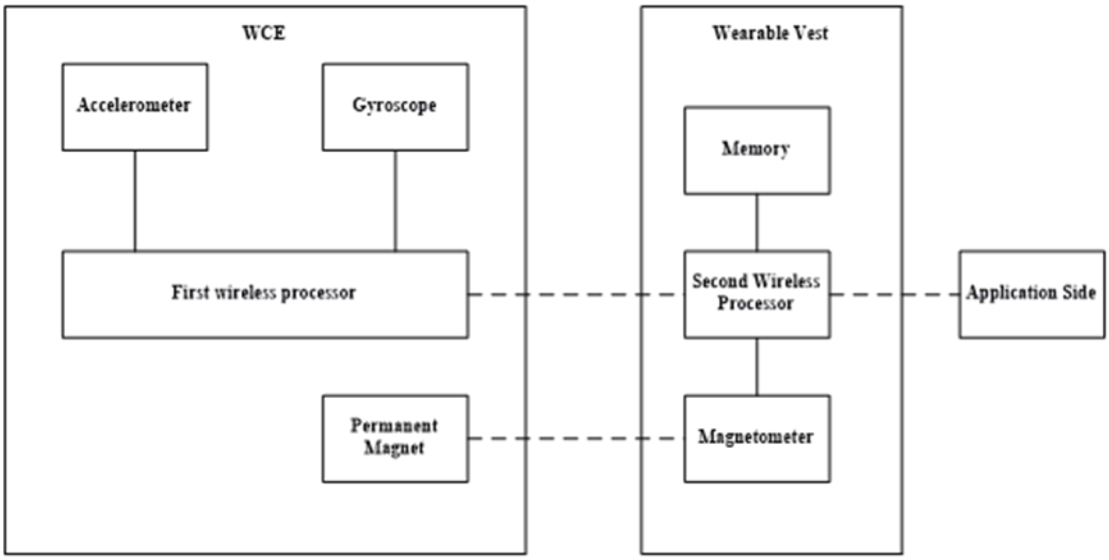

Figure 8. IMU-magnetic sensor fusion pipeline

4. CONCLUSION

This article reviews the state of art in capsule endoscopy positioning technology based on magnetic sensors, and evaluates the application value from feasibility and reliability. Then, it points out several future trends, including the multi-sensor information fusion, and development positioning algorithm under harsh conditions. Finally, it takes an example of development approach to verify the validity of these future trends.

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